Second Italian Workshop on the Physics at High Intensity

Rome,
8–10 November 2023

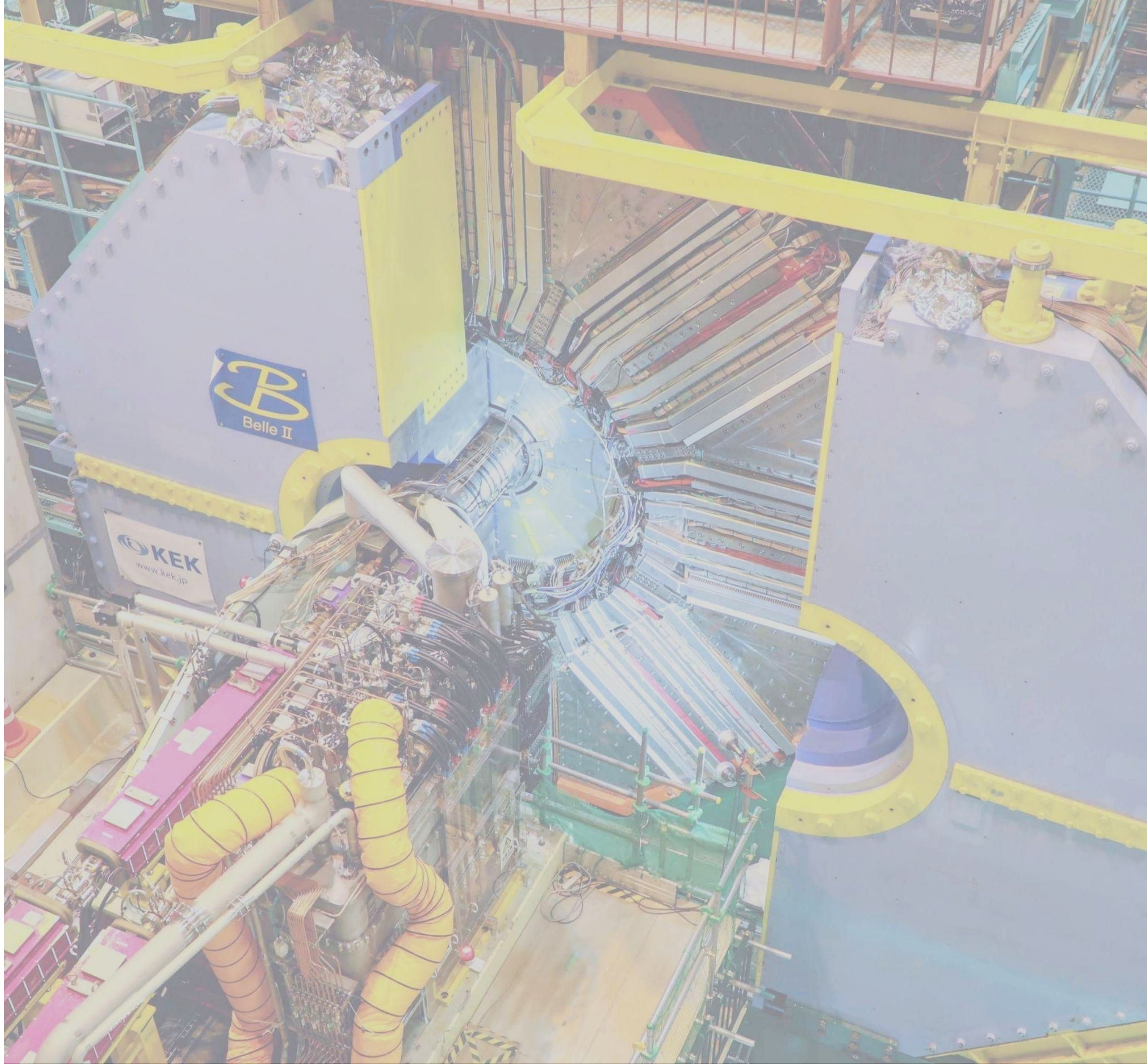
Spectroscopy at Belle II

A. Boschetti

Belle II

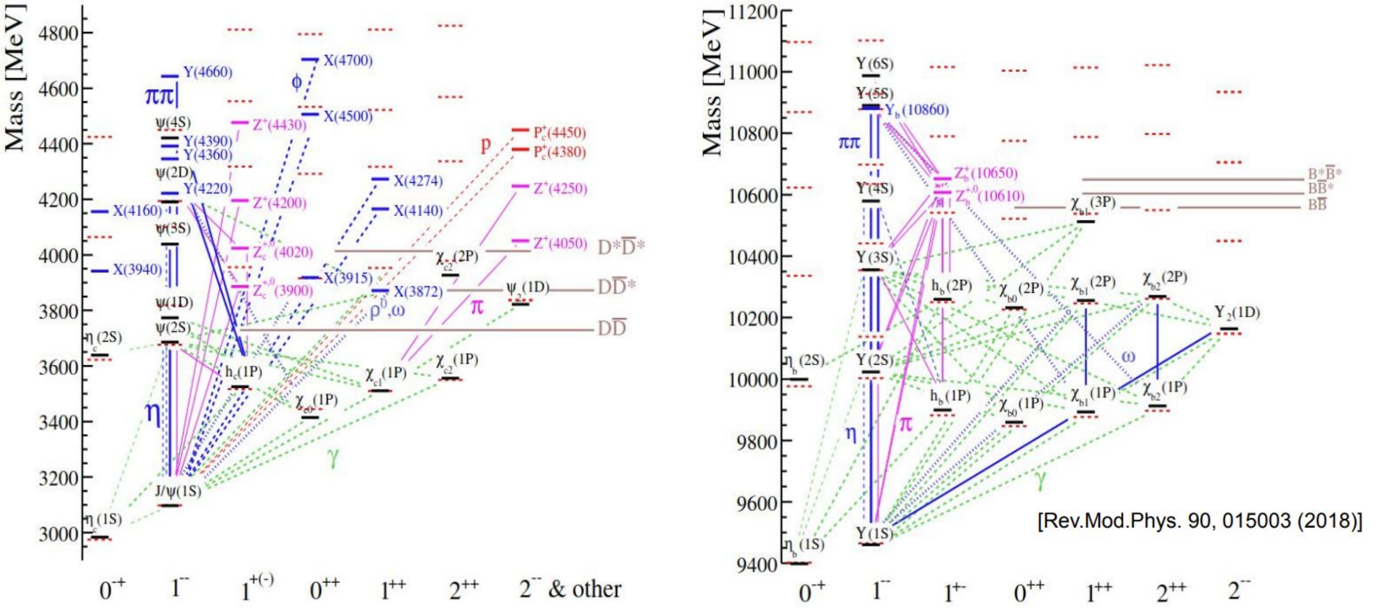
UNIVERSITÀ DI TORINO

INFN TORINO



The rebirth of hadron spectroscopy

- Lots of unexpected, puzzling experimental results
  - especially in **heavy quarkonium** sector
- Difficulties in QCD calculations hinder accurate predictions for spectra
- Interplay of **experimental results** and **effective models/LQCD** is needed

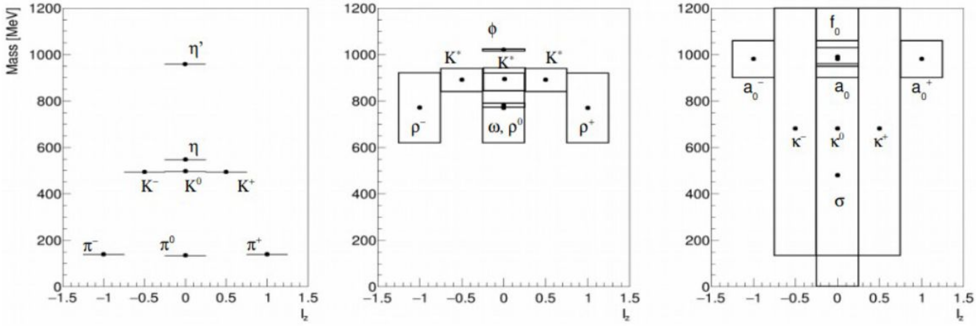


[Rev.Mod.Phys. 90, 015003 (2018)]

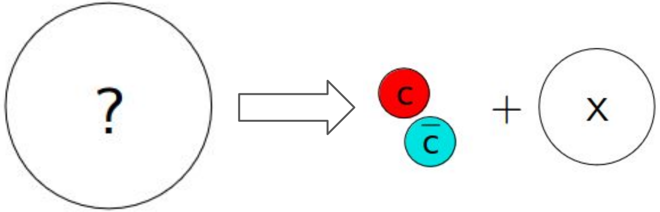
Why heavy hadrons

Multi-quark systems are possible at any energy [Jaffe, Wilkez, PRL 91 232003 (2003)]

However, no smoking gun to distinguish $q\bar{q}$ from $qq\bar{q}\bar{q}$ in light sector



With **heavy quarks** separating conventionals and exotics is much simpler, e.g.



- Mass > 3 GeV/c^2
- Small width (Γ/M < 0.1)
- Large BF for J/ψ (or $D\bar{D}$) + X decay

⇒ Must contain $c\bar{c}$ pair

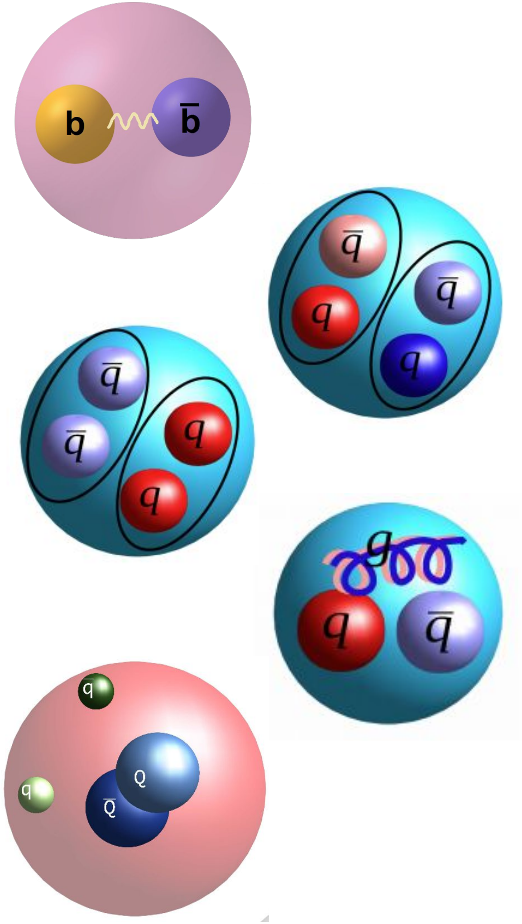
XYZ states

What are they? Several models compete:

- **Standard quarkonia** [Swanson, PRD 91, 034009 (2015)]
- **Meson molecules**: shallow bound states of two mesons [Guo *et al.*, Rev.Mod.Phys.90,015004 (2018)]
- **Compact tetraquarks**: diquark-antidiquark states bound by the color force [Polosa *et al.*, PRD89, 114010 (2014)]
- **Hybrids**: colored QQbar states with bound excited gluon [Meyer and Swanson, Prog.Part.Nucl.Phys. 82, 21 (2015)]
- **Hadroquarkonium**: QQbar state surrounded by a cloud of light quarks [Dubinskij *et al.*, PLB 666, 344 (2008)]

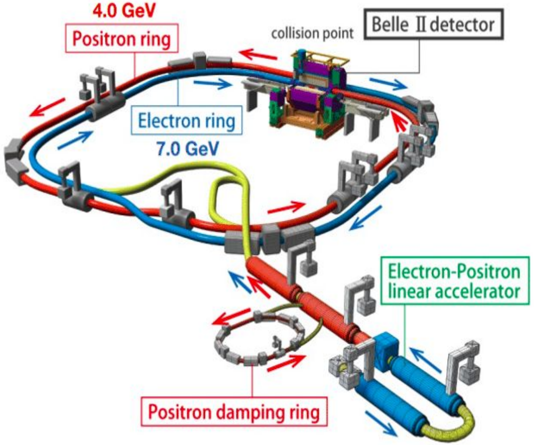
Comprehensive reviews

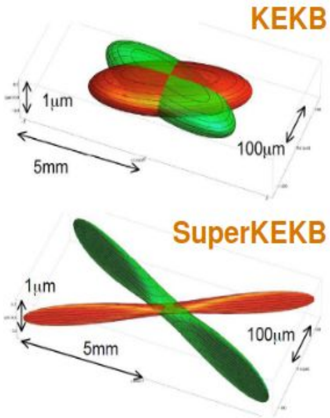
- Brambilla *et al.*, Eur. Phys. J. C (2011) 1534
- Olsen *et al.*, Rev. Mod. Phys. 90 (2018) 015003

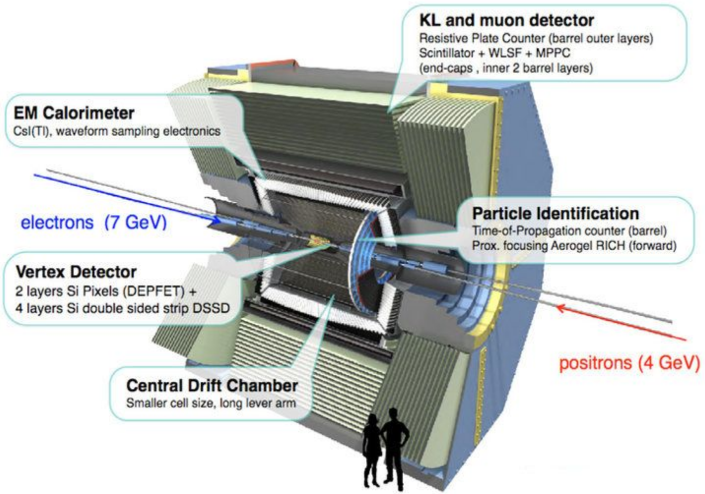


Belle II at SuperKEKB

- Super B-factory ⇒ optimized for $\Upsilon(4S)$
- Quarkonium spectroscopy
  - **Tunable beam energy**: from $\Upsilon(1S)$ to $\Upsilon(6S)$
  - Projected **luminosity ~ 40x** wrt previous B-factory

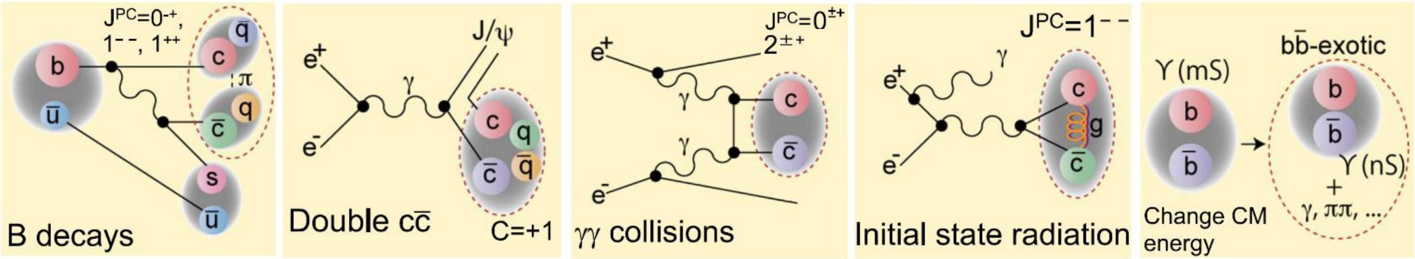






Quarkonium at Belle II

- Production

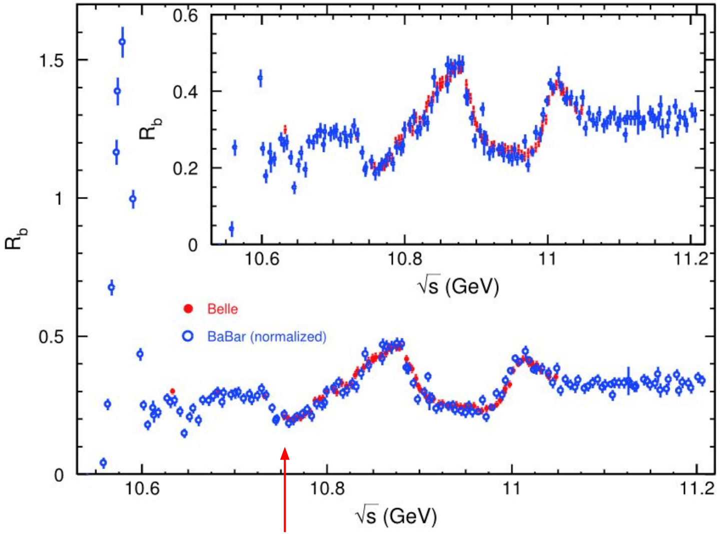


- Decays
  - Hidden flavor **transitions**: radiative, hadronic
  - **Decays**: above threshold ⇒ open flavor | below threshold ⇒ leptonic, hadronic
- Analysis techniques
  - **Exclusive**: complete decay reconstruction ⇒ very clean samples
  - **Quasi-exclusive**: Full Event Interpretation (FEI) ⇒ sum of exclusive modes
  - **Inclusive**: missing momentum. Knowledge of collision energy ⇒ full reco not required ⇒ high ε

Above Υ(4S) scans

High energy scans @ Belle and BaBar ⇒ R_b

- Peaks at 10.86 and 11.02 GeV ⇒Υ(5S), Υ(6S)
- Dips at 10.65, 10.75 GeV

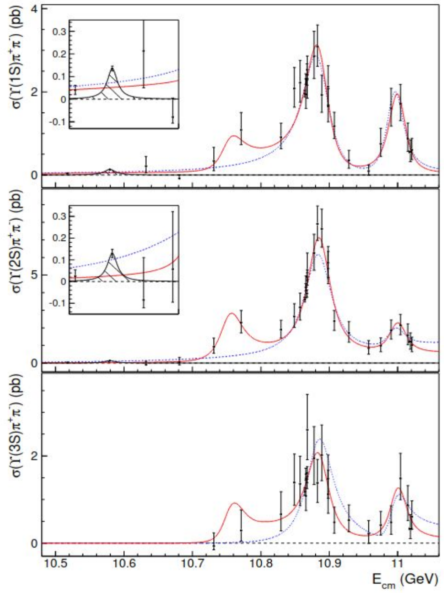


Discovery of Υ(10753) in ππ transitions

σ(Υ $\pi^+\pi^-$): peaks at 10.89, 11.02 GeV

Bump at 10.75 GeV ?

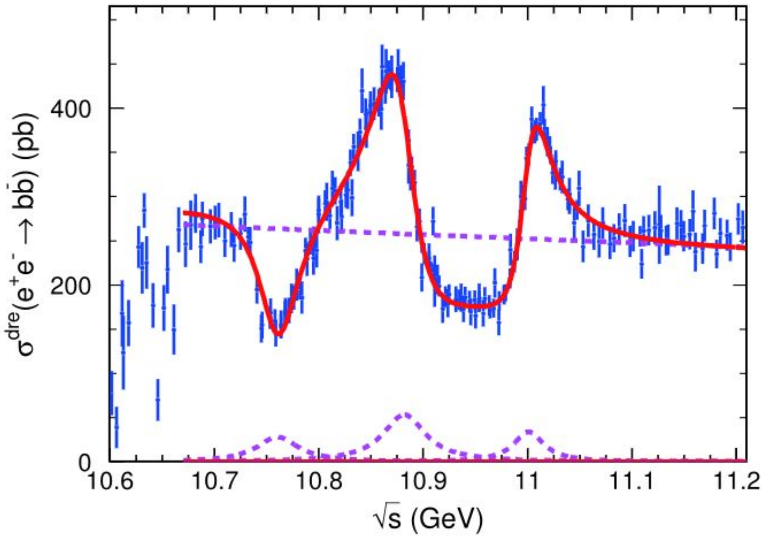
We want to know more about the nature of this structure



[Belle, JHEP 10 (2019) 220]

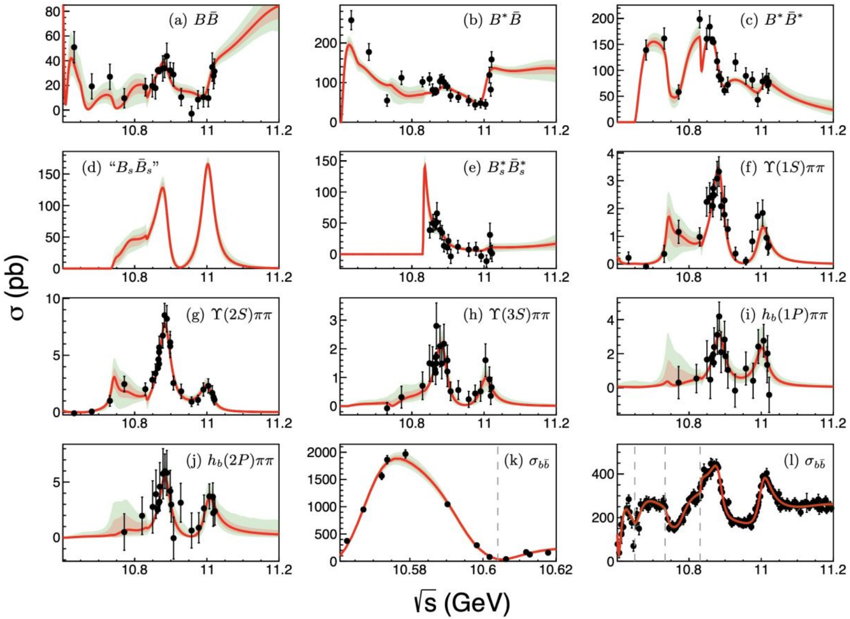
Fitting the R_b scans

Coherent sum of continuum and 3 BW functions
[Dong *et al.*, Chin. Phys. C 44 (2020) 8, 083001]



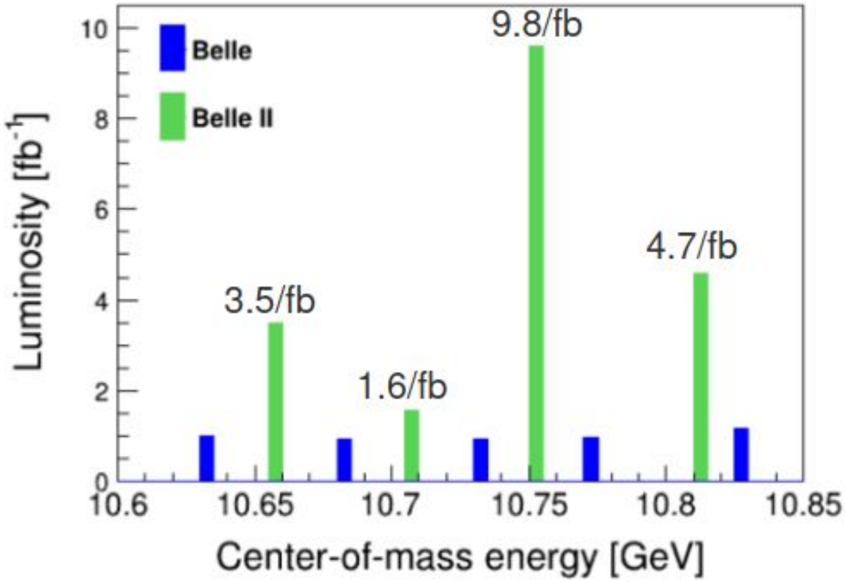
Parameter	$Y(10750)$	$\Upsilon(5S)$	$\Upsilon(6S)$
Mass/(MeV/c^2)	10761 ± 2	10882 ± 1	11001 ± 1
Width/MeV	48.5 ± 3.0	49.5 ± 1.5	35.1 ± 1.2

Coupled channel analysis using the **K matrix** formalism
[Hüsken *et al.*, PRD 106 (2022) 9, 094013]



SuperKEKB high energy scan data

~4 times the Belle luminosity between [10.6, 10.85] GeV has been recently collected (2021)



Belle II analyses

Observation of $Y(10753) \to \omega\chi_{bJ}(1P)$

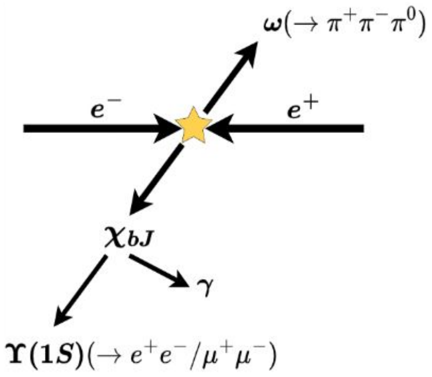
Motivated by prediction for S–D mixed state [PRD 104 034036 (2021)]:

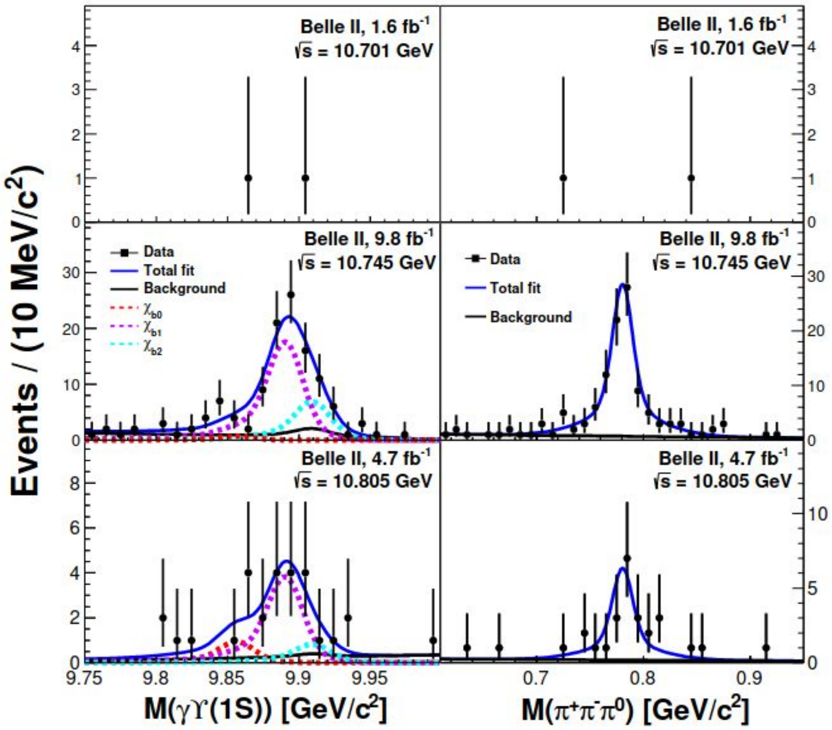
BR comparable with $Y_b \to \pi^+\pi^- \Upsilon(nS)$,

$$\frac{\mathcal{B}(\omega\chi_{b1})}{\mathcal{B}(\omega\chi_{b2})} \sim \frac{1}{5}$$

Inspired by the decay modes observed by BESIII:

- $Y(4230) \to \chi_{c0}(1P)\omega$
- $Y(4230) \to \gamma X(3872)$

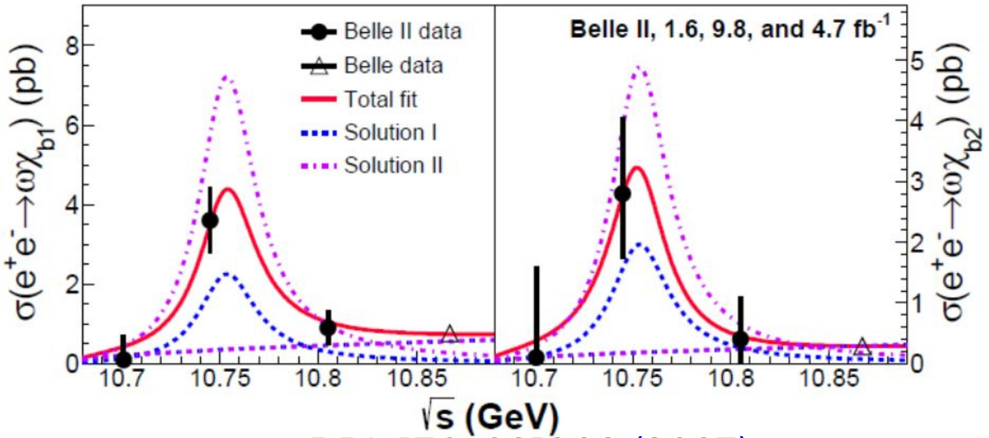




PRL 130, 091902 (2023)

Observation of Y(10753) → $\omega\chi_{bJ}(1P)$

- The signal is larger than in
  Y(10753) → ϒ(2S)π+π-
  (Compare with ϒ(5S))



PRL 130, 091902 (2023)

- The signal at ϒ(5S) is likely a **tail**

- Two $J^{PC} = 1^{--}$ states, ΔM = 120 MeV, 1 order of magnitude diff in σ ⇒ hints at **different structure**

$$\frac{\sigma(e^+e^-\to\chi_{b1}(1P)\omega)}{\sigma(e^+e^-\to\chi_{b2}(1P)\omega)} = 1.3\pm0.6$$

Pure ϒ(3D) would give 15 [Guo *et al.*, PLB 738 (2014), 172]
Slight tension with mixed 4S-3D state
[Li *et al.*, PRD 104 (2021) 034036]

Search for X_b

X_b = bottomonium analogue of X(3872)

Existence predicted in both molecular and tetraquark models

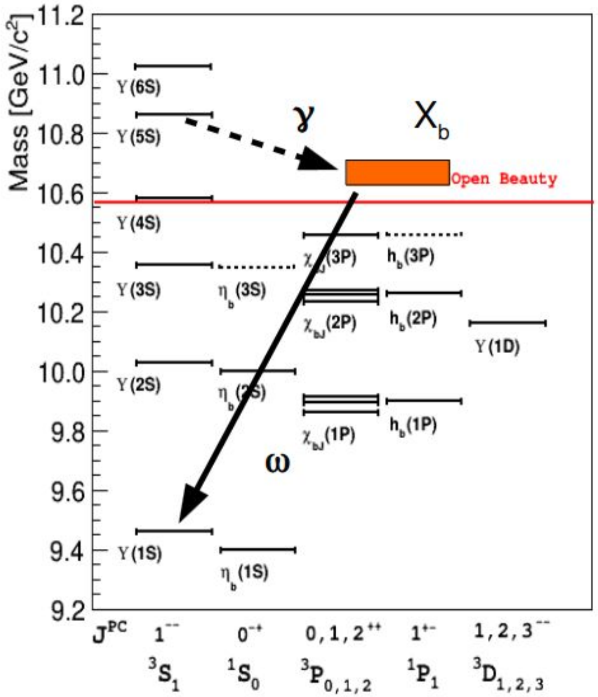
- Molecule ⇒ M close to $B\bar{B}^*$ threshold
- Tetraquark ⇒ $10 < M < 11$ GeV/c^2

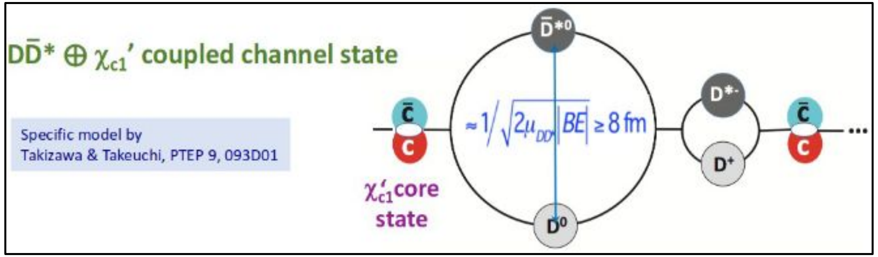
No χ_b near $B\bar{B}^*$ threshold ⇒ No X_b?

Strong UL on σ ⇒ exclude tetraquark hypothesis

Negligible isospin breaking for X_b

⇒ **3π mode enhanced** wrt 2π

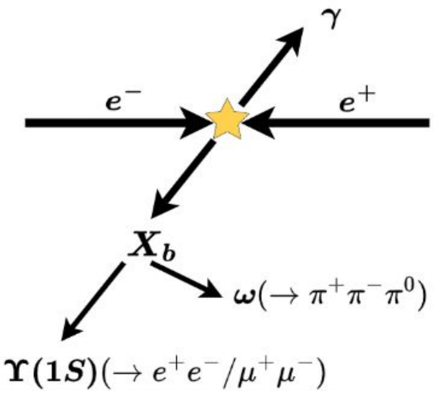


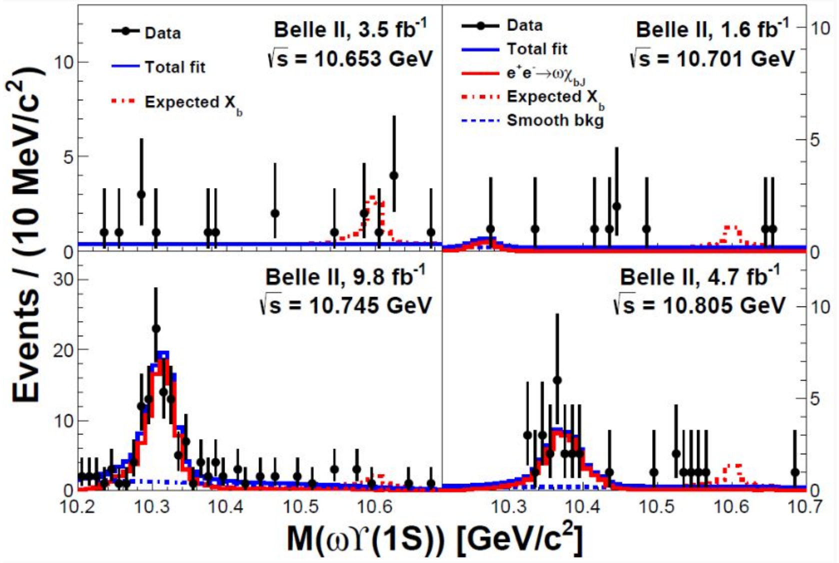


Search for X_b

- Same $\Upsilon(1S)\ \pi^+\pi^-\pi^0\ \gamma$ final state
- Search for resonances in $M(\Upsilon(1S)\omega)$
- Reflection from $Y(10753) \to \omega\chi_{bJ}(1P)$
- No evidence for X_b signal

$\sqrt{s}$ (GeV)	M_{X_b} (GeV)	$\sigma^{UL}_{X_b}$ (pb)
10.653	10.59	0.55
10.701	10.45	0.84
10.745	10.45	0.14
10.805	10.53	0.47





PRL 130, 091902 (2023)

Search for $\Upsilon(10753) \rightarrow \chi_{b0}(1P)\omega$, $\eta_b(1S)\omega$

Motivation

- Tetraquark model ⇒ strong enhancement for $\Upsilon(10753) \rightarrow \eta_b(1S)\omega$ (30x $\Upsilon(2S)\pi^+\pi^-$)

  [CPC 43 (2019) 12, 123102]

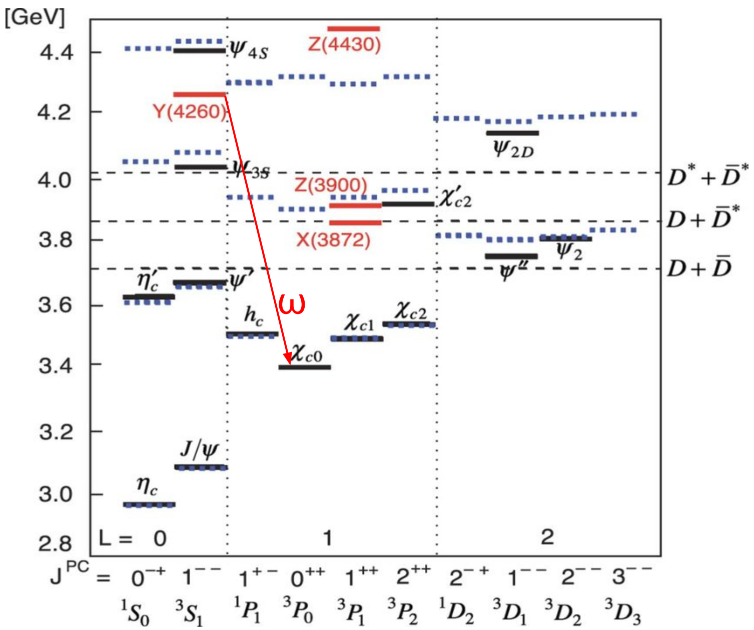
- Observation of enhancement for

  $\psi(4220) \rightarrow \chi_{c0}(1P)\omega$ wrt

  $\psi(4220) \rightarrow \chi_{c1,2}(1P)\omega$

  [BESIII, PRD 99 (2019) 091103]

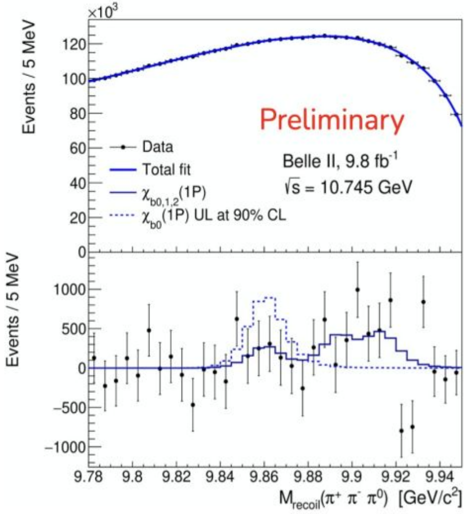
$\chi_{b0}(1P)$ and $\eta_b(1S)$ don't have few body decays w/ high BF ⇒ **inclusive analysis**

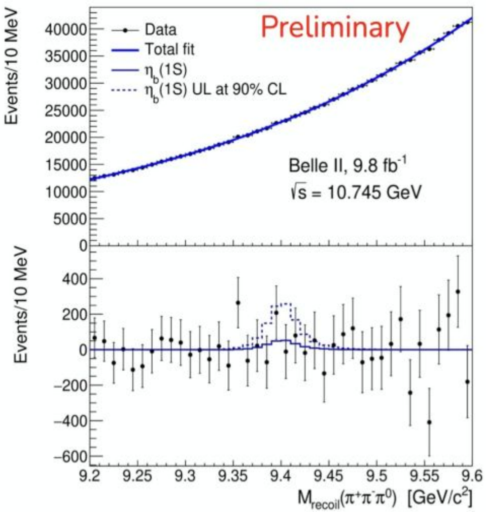


$$M_{\text{recoil}}(\pi^+\pi^-\pi^0) = \sqrt{\left(\frac{E_{\text{c.m.}} - E^*}{c^2}\right)^2 - \left(\frac{p^*}{c}\right)^2}$$

Search for $Y(10753) \to \chi_{b0}(1P)\omega$, $\eta_b(1S)\omega$

Fit to $M_{recoil}(\pi^+\pi^-\pi^0)$ ⇒ no significant signal observed, 90% CL upper limits are set





$\sigma(e^+e^- \to \chi_{b0}(1P)\omega) < 8.7$ pb

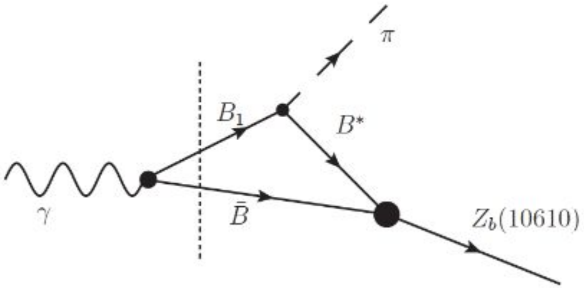
$\sigma(e^+e^- \to \eta_b(1S)\omega) < 2.5$ pb
compare w/ $\sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-) \sim 2.0$ pb
[JHEP 10 (2019) 220]

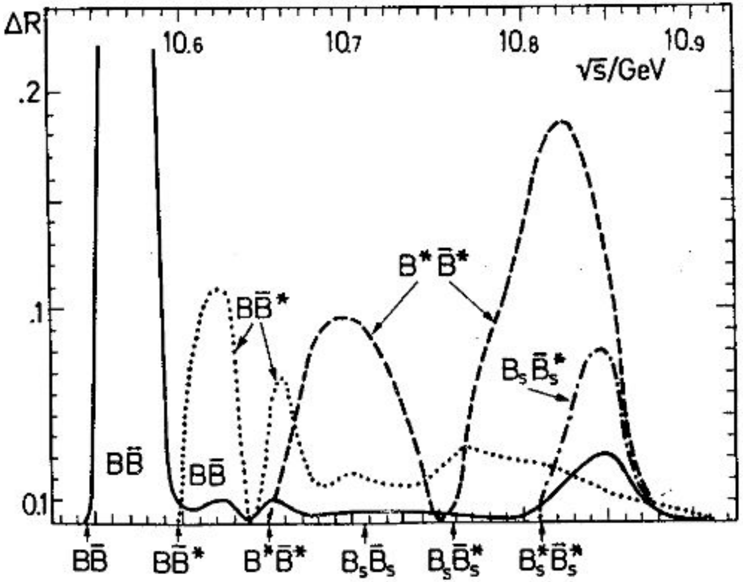
Results do not support the tetraquark model in [CPC 43 (2019) 12, 123102]

$e^+e^- \to B\bar{B} + B\bar{B}^* + B^*\bar{B}^*$ cross sections

Motivation

- Investigate properties for all bottomonia near/above threshold
  - ⇒ Υ(10753) partial widths
- First ingredients for **coupled channel analysis** of exclusive modes
- Add new scan points for R_b fits
- Part of broad program to measure exclusive cross sections





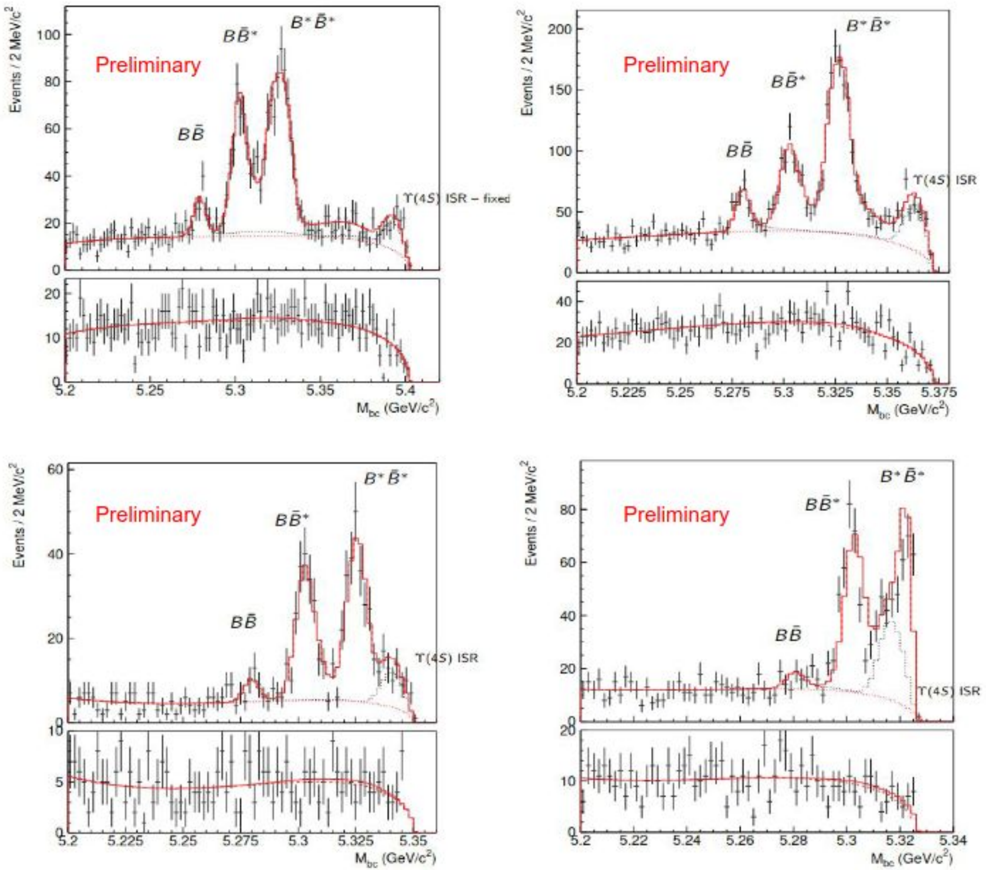
Tornqvist, PRL 53 (1984) 878

$e^+e^- \to B\bar{B} + B\bar{B}^* + B^*\bar{B}^*$ cross sections

Method

- FEI: fully reconstruct one B
- Identify signals with M_{bc}
- Combine with Belle measurement [JHEP 06, 137 (2021)]

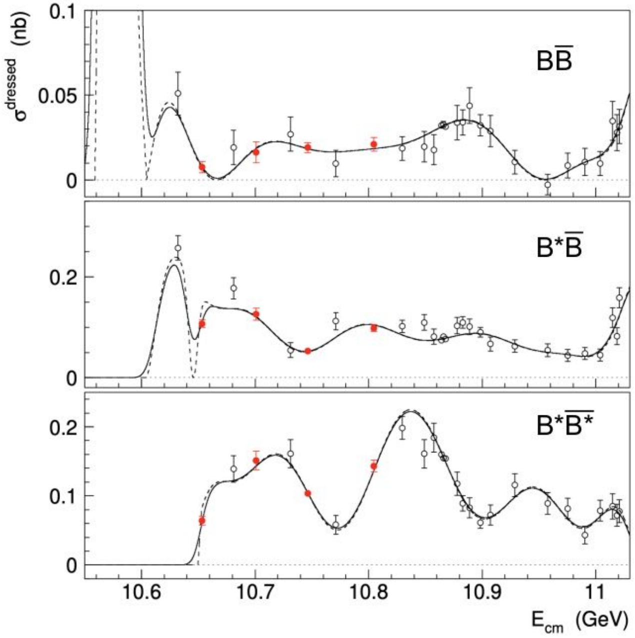
$$M_{\rm bc} = \sqrt{(E_{\rm cm}/2)^2 - p_B^2}$$



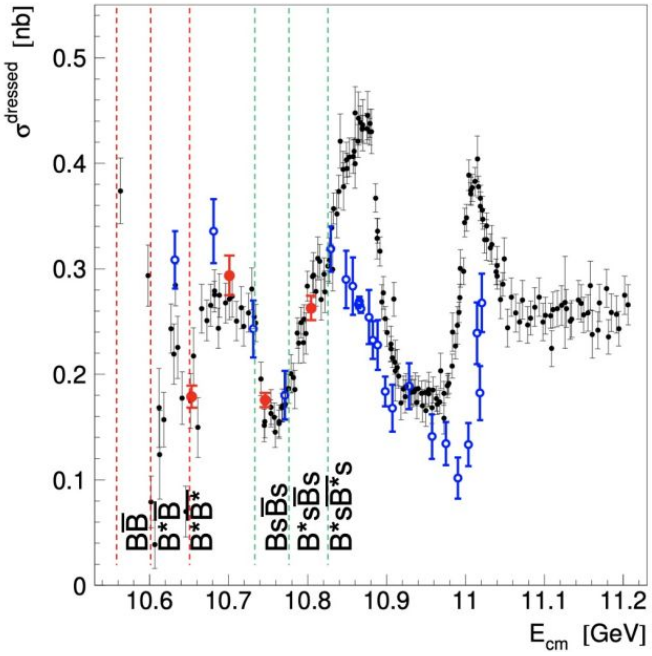
$e^+e^- \to B\bar{B} + B\bar{B}^* + B^*\bar{B}^*$ cross sections

2-body cross sections fit with Chebychev polynomials

Steep rise of the $B^*\bar{B}^*$ cross section at threshold
⇒ hint at existence of bound state

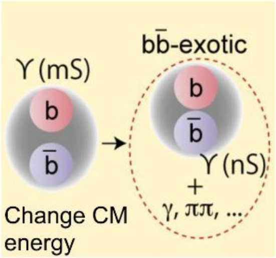


Shown at Moriond QCD 2023
(See Michel Bertemes' talk)
To appear on JHEP



Belle [Sci.Bull. 65 (2020) 23, 1983]
Belle II new points

Belle II potential: high energy scan

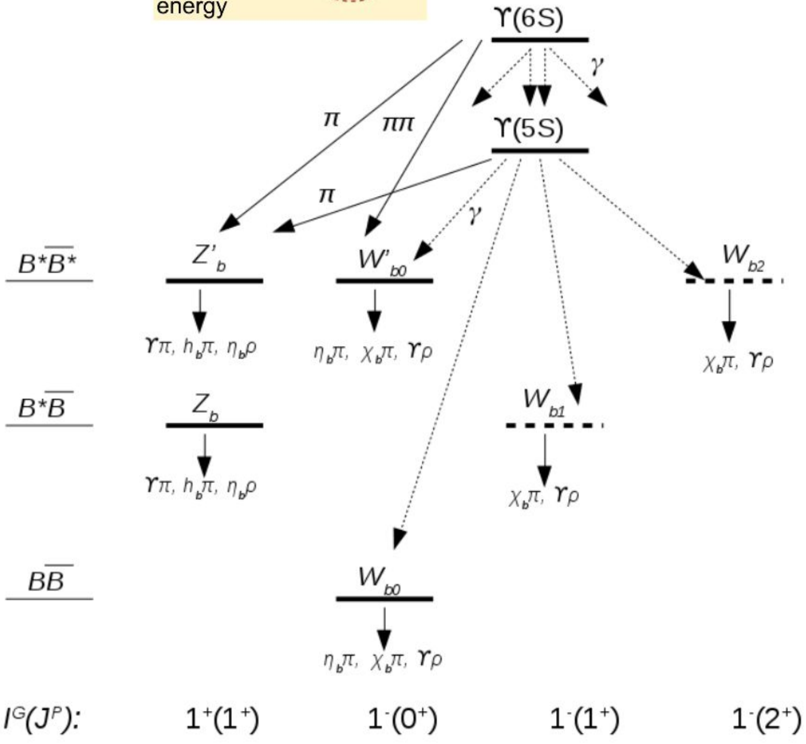


Only 5 fb^{-1} integrated by Belle at ϒ(6S) (five points)

Small dataset compared to ϒ(5S) (121.4 fb^{-1})

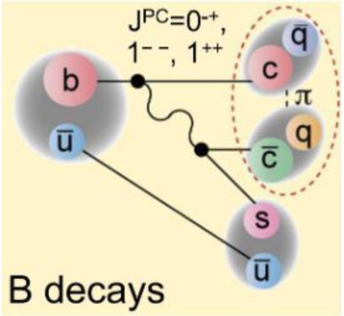
With more data:

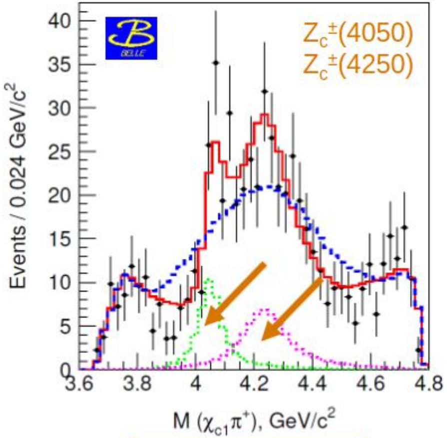
- Search for **missing conventional bottomonia**
  - spin-singlets in 3S, 3P, 1D multiplets
- Measure η and ππ transitions BFs
  - **HQSS violation**, molecular states
- If Z_b is a molecule, partners must appear
  - γ, ρ transitions
  - **no predictions on W_b production** rate
- Strange partners Z_{bs} ?
  - $e^+e^- \to Z_{bs} K \to KK (b\bar{b})$ (~11.2 GeV)
- ...



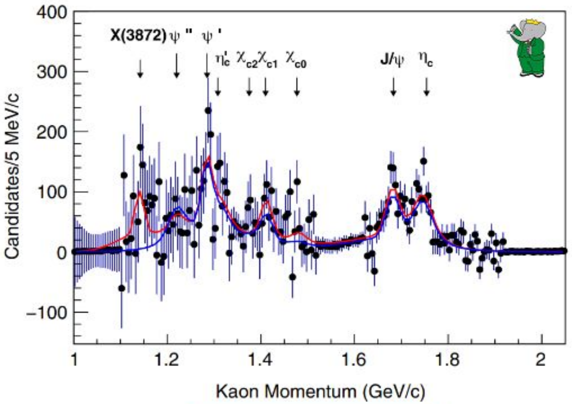
Belle II potential: B decays

- High-statistics continuation from B-factories
- Competition from LHCb: advantages for modes with neutrals
  - Confirm Z_c states and search for neutral partners
  - Absolute branching ratios for B → X(3872,3915) K
  - X(3872) width and lineshape measurement with $D^0\overline{D}^0\pi^0$

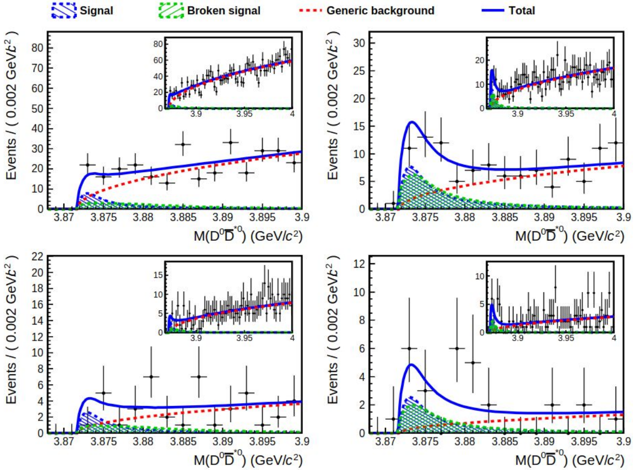




PRD 78, 072004 (2008)

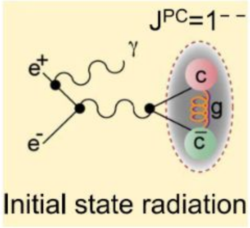


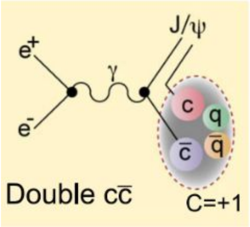
PRL 124, 152001 (2020)

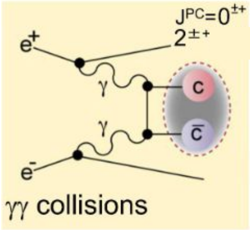


PRD 107, 112011 (2003)

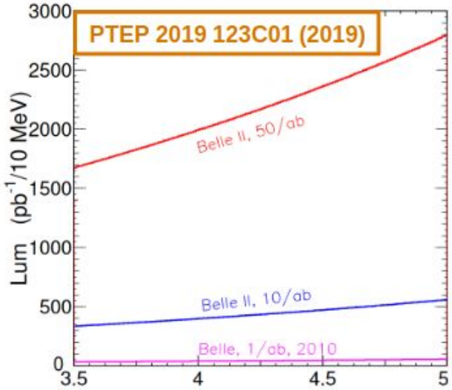
Belle II potential: other processes

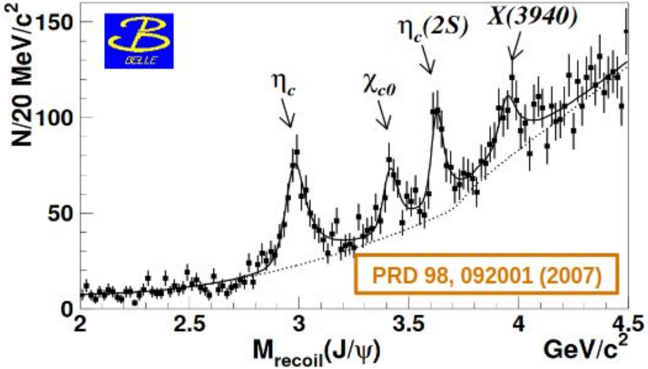


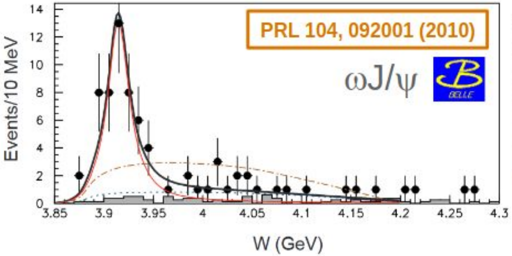


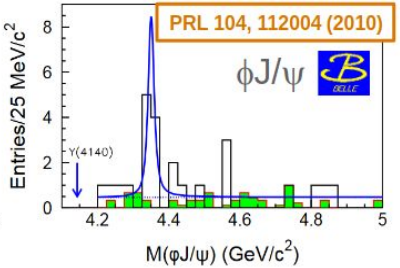


- ISR
  - Continuous mass range above 4.9 GeV/c^2
  - Higher masses/channels
  - Z_c states (e.g. e+e- → $h_c\pi\pi$)
- Double charmonium
  - e+e-→$(ccbar)_{J=1}(ccbar)_{J=0}$ production rule
  - Discovery of X(3940, 4160)
  - Expand to other new states
- Two-photon
  - J^{PC} of X(3915)
  - Confirm φJ/ψ state?
  - $D^{(*)}Dbar^{(*)}$final states





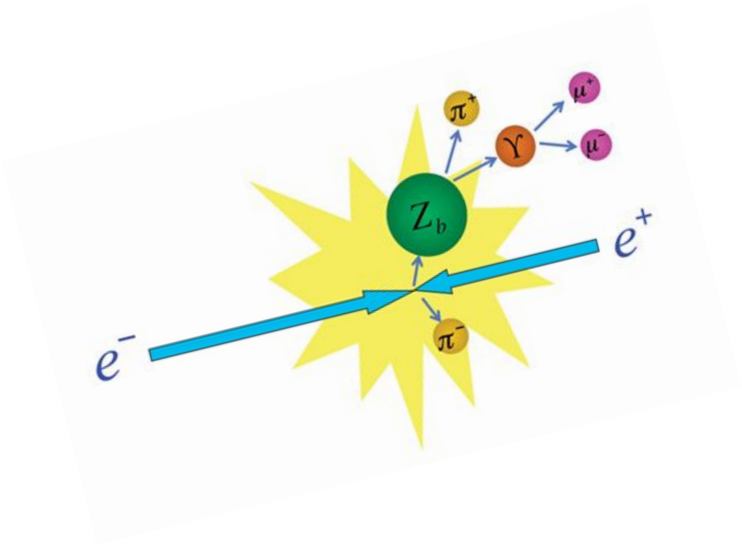




In conclusion

- The advent of B factories has led to a renaissance of hadron spectroscopy
- Belle II is one of the experimental pillars in the quarkonium sector
    - some production modes are **unique** to Belle II
- The recent **scan data** is starting to show interesting results

Stay tuned for many more to come!



Backup

Promising e+e- energy regions

Molecular states are naturally located (and produce the largest effects) near the corresponding threshold

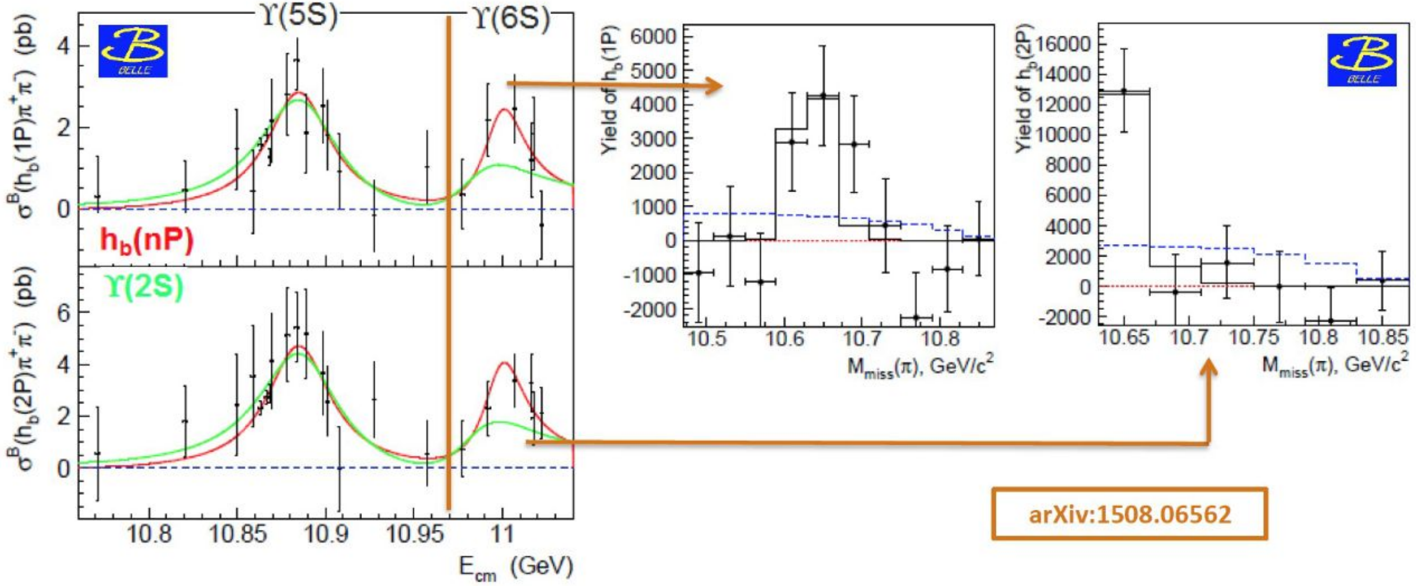
Particles	Threshold, GeV/c^2
$B^{(*)}\bar{B}^{**}$	11.00 – 11.07
$B_s^{(*)}\bar{B}_s^{**}$	11.13 – 11.26
$\Lambda_b\bar{\Lambda}_b$	11.24
$B^{**}\bar{B}^{**}$	11.44 – 11.49
$B_s^{**}\bar{B}_s^{**}$	11.48 – 11.68
$\Lambda_b\bar{\Lambda}_b^{**}$	11.53 – 11.54
$\Sigma_b^{(*)}\bar{\Sigma}_b^{(*)}$	11.62 – 11.67
$\Lambda_b^{**}\bar{\Lambda}_b^{**}$	11.82 – 11.84

Within current SuperKEKB reach

Baryon-antibaryon molecules?
Need to increase max E_{cm} …

Υ(6S) results in Belle-I

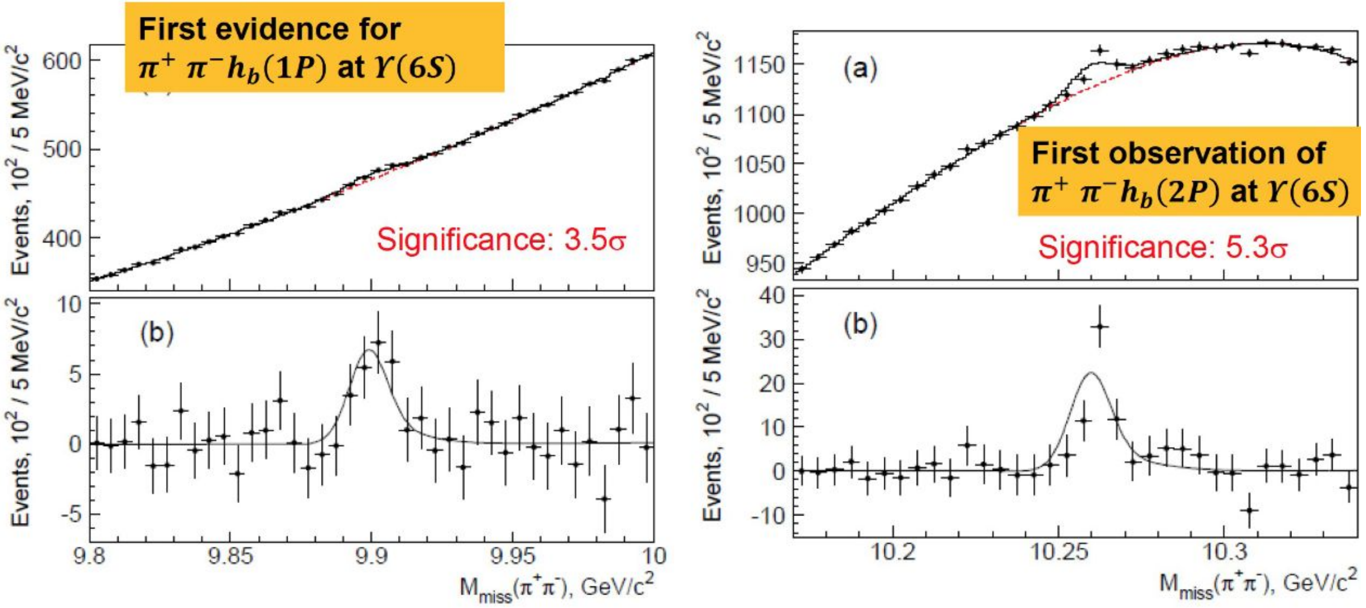
- Preliminary evidence for $\Upsilon(6S)\to\pi\pi h_b(nP)$, via $\pi Z_b^{\pm}(106XX)$ decay



arXiv:1508.06562

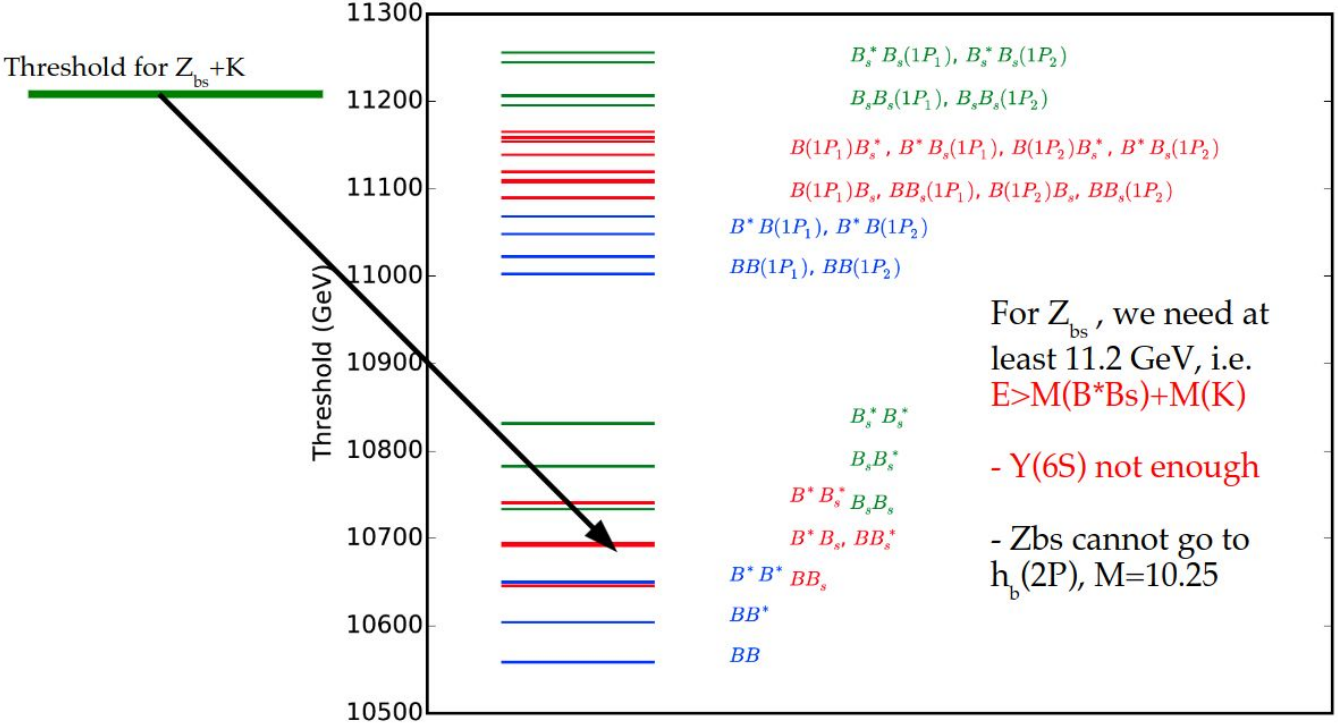
- Resonance structure of $\Upsilon(6S)\to\pi\pi\Upsilon(pS)$ decays not fully studied

Υ(6S) results in Belle-I



Significance figures include syst errors

Z_{bs} searches in Belle-II



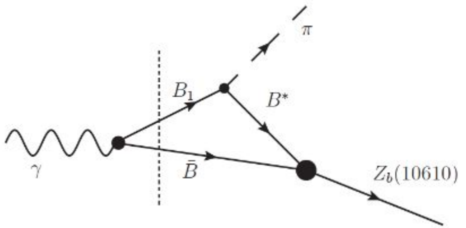
Υ(6S) prospects in Belle-II phase II

(Voloshin at B2TIP-2016)

- With current (limited) statistics at $\Upsilon(6S)$ ($\sim$ 11.00 GeV):

$$\left.\frac{\Upsilon(nS)\pi\pi}{h_b(kP)\pi\pi}\right|_{\Upsilon(6S)} \approx \left.\frac{\Upsilon(nS)\pi\pi|_{\text{through}Z_b}}{h_b(kP)\pi\pi}\right|_{\Upsilon(5S)}$$

  I.e. at $\Upsilon(6S)$ essentially no non-resonant background not associated with $Z_b^{(\prime)}$, unlike at $\Upsilon(5S)$. (The HQSS 'forbidden' channels $h_b(kP)\pi\pi$ go exclusively through the $Z_b^{(\prime)}$ within either peak.)
- 11006 MeV is the threshold for $B_1(5721)\bar{B}$. If the pair is produced near threshold, then a 'threshold triangle singularity' is possible with



  $Z_b(10610)$ [not the $Z_b(10650)$].

5th Belle-II Italian Meeting R.Mussa, Bottomonium Physics at Belle-II

QCD in a nutshell

QCD is the theory of quark and gluon interactions

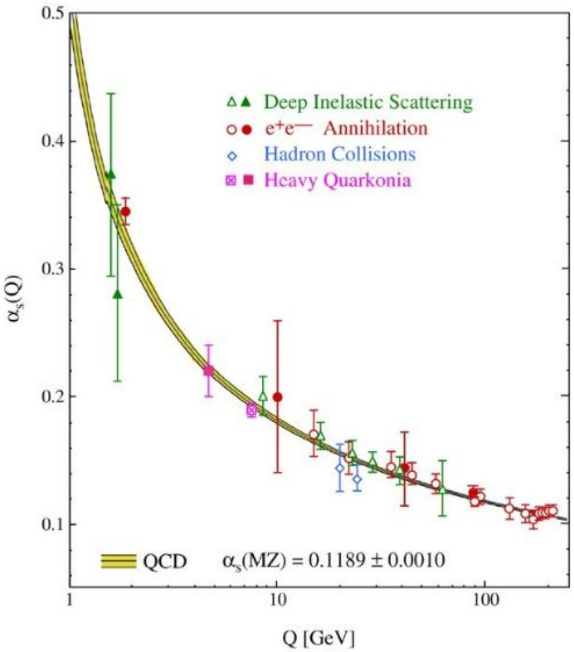
- SU(3) symmetry
  - 8 gauge bosons, 3 charges

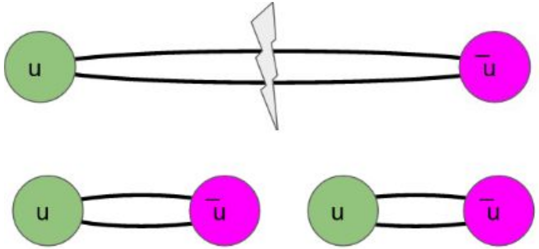
Asymptotic freedom

- weaker interaction at higher energies
- non-perturbative regime at low energies

Confinement

- quarks are always confined inside color neutral particles (hadrons)





QCD in a nutshell

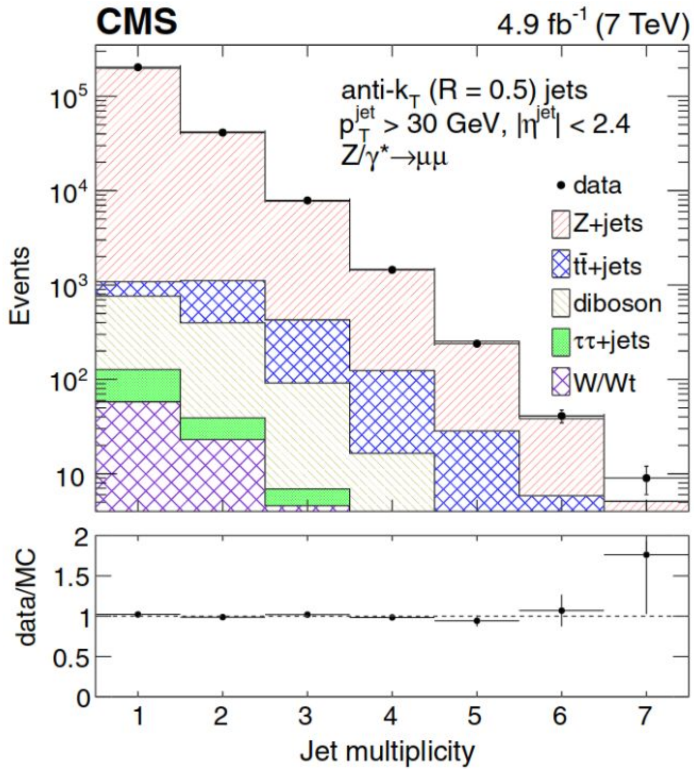
QCD is the theory of quark and gluon interactions

- SU(3) symmetry
  - 8 gauge bosons, 3 charges

<u>Perturbative QCD works very well</u>

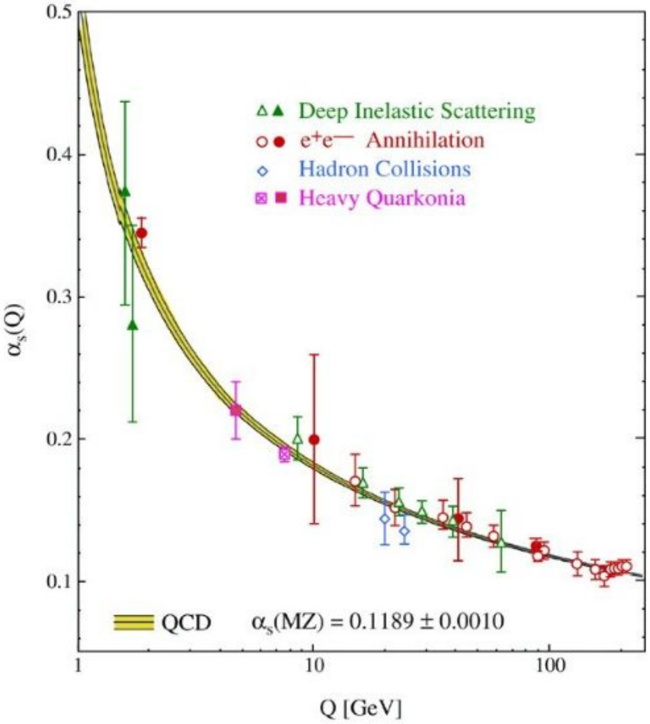
However

- not the regime in which matter is formed
- not the regime in which meson and baryon structures arise



Facing non-perturbative QCD

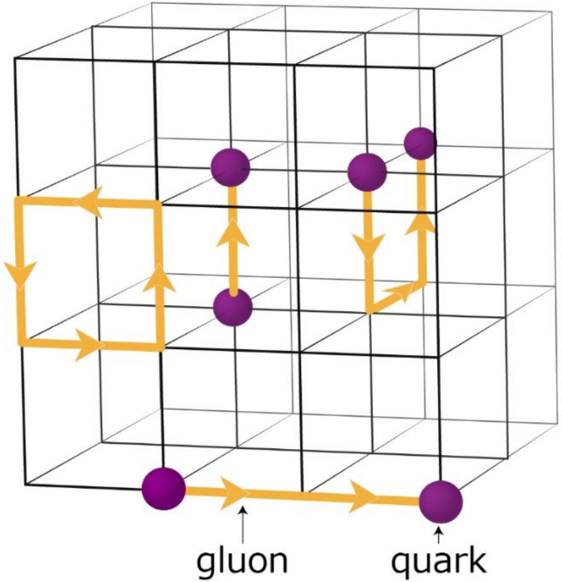
α_s is not a good expansion parameter to study bound states



Facing non-perturbative QCD

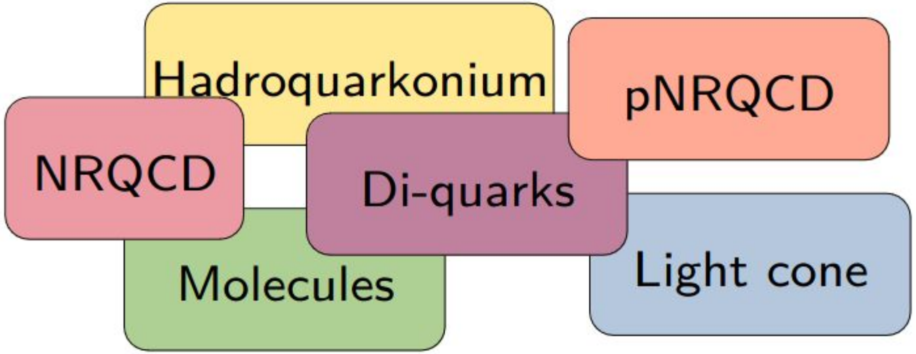
α_s is not a good expansion parameter to study bound states

Solve QCD numerically (on the lattice)

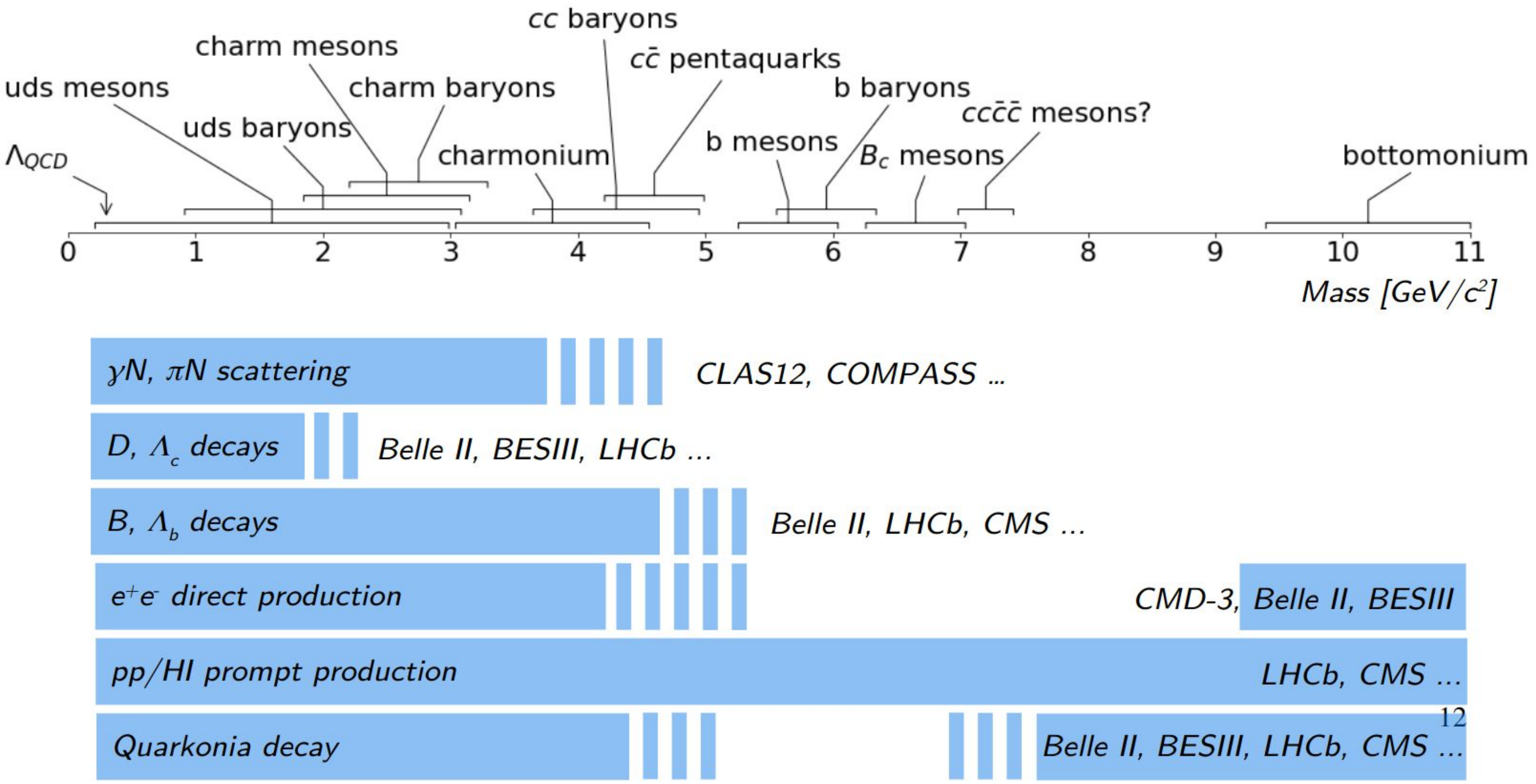


+

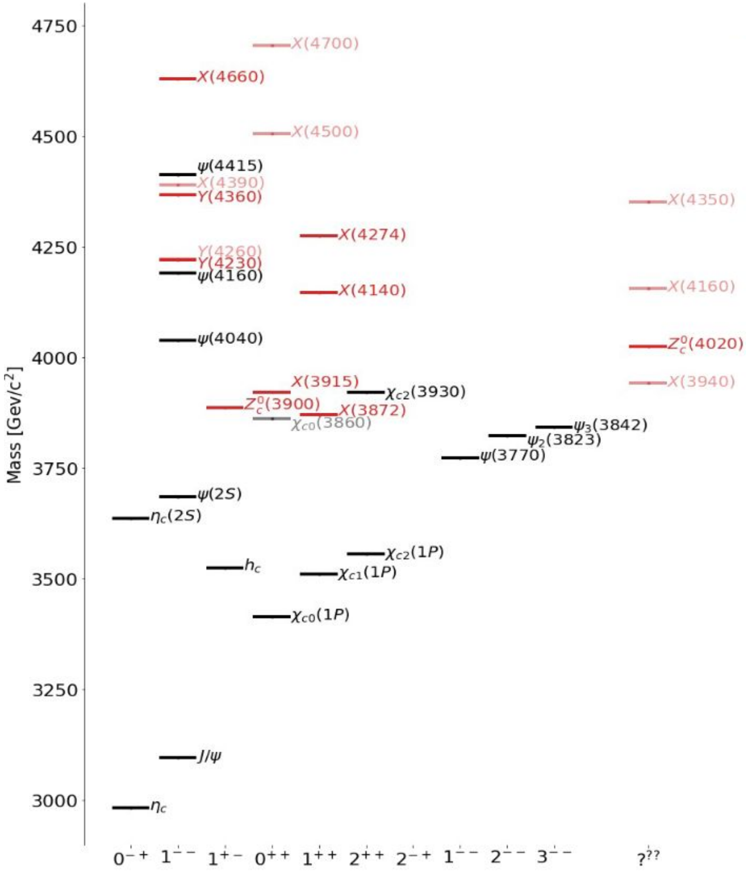
Use effective theories



Heavy and light hadrons



Exotics: where we are



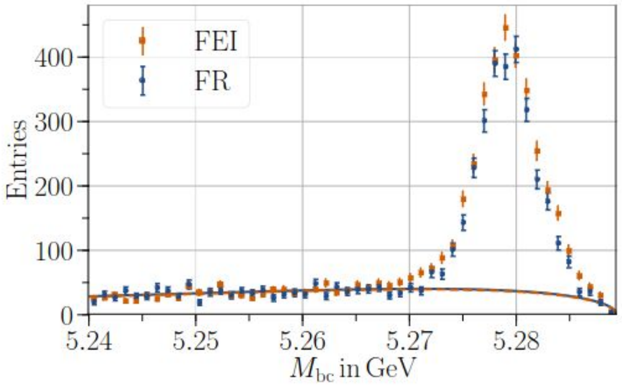
In 15 years we discovered

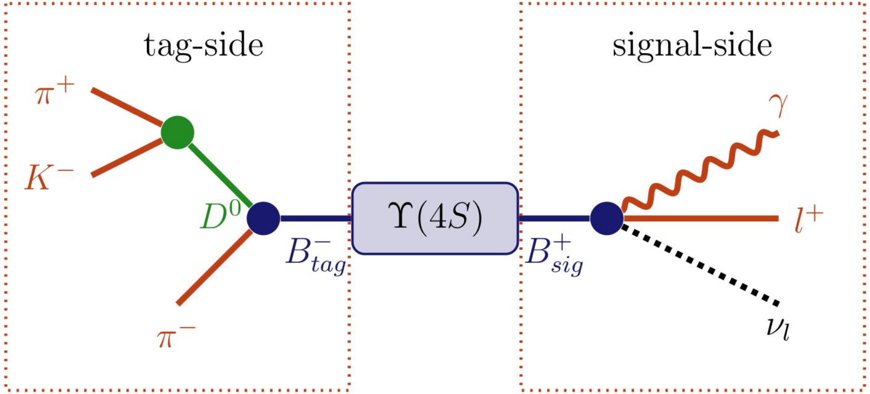
- ~ 30 exotics in charmonium
- 3 exotics in bottomonium
- 5 pentaquarks

Full Event Interpretation

Classifier value P_{tag} discriminates correctly reconstructed tag-sides from background

Determine the correctly reconstructed tag-side yield by fitting M_{bc}





- Reconstruct one B meson as tag-side (B_{tag}) hadronic or SL
- Study remaining B meson as signal (B_{sig})

Full Event Interpretation

Utilises O(200) decay channels with a classifiers trained for each

Reconstructs O(10000) unique decays chains in six stages